

MEASURING NEUTRINO MASSES WITH SUPERNOVA NEUTRINOS *

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A new method to study the effects of neutrino masses on a supernova neutrino signal is proposed. The method relies exclusively on the analysis of the full statistics of neutrino events, it is independent of astrophysical assumptions, and does not require the observation of any additional phenomenon to trace possible delays in the neutrino arrival times. A statistics of several thousands of events as could be collected by SuperKamiokande, would allow to explore a neutrino mass range somewhat below 1 eV.

1. Introduction

Already long time ago it was realized that Supernova (SN) neutrinos can provide valuable informations on the neutrino masses.¹ The basic idea relies on the time-of-flight delay Δt that a neutrino of mass m_ν and energy E_ν traveling a distance L would suffer with respect to a massless particle:

$$\frac{\Delta t}{L} = \frac{1}{v} - 1 \approx \left(\frac{5.1 \text{ ms}}{10 \text{ kpc}} \right) \left(\frac{10 \text{ MeV}}{E_\nu} \right)^2 \left(\frac{m_\nu}{1 \text{ eV}} \right)^2, \quad (1)$$

where for ultra-relativistic neutrinos $1/v = E_\nu/p_\nu \simeq 1 + m_\nu^2/2E_\nu^2$ was used. The dispersion in the arrival time of about twenty $\bar{\nu}_e$ from supernova SN1987A was used in the past to set the model independent limit $m_{\bar{\nu}_e} < 30 \text{ eV}$,² while a recent detailed reanalysis obtained, within the SN delayed explosion scenario, $m_{\bar{\nu}_e} < 5.7 \text{ eV}$.³ Since SN1987A, several efforts have been carried out to improve the sensitivity of the method, while awaiting for the next Galactic SN explosion. Often, these approaches rely on “timing” events related to the collapse of the star core, that are used as benchmarks for measuring the neutrino delays. The emission of gravitational waves,^{4,5} the ν_e neutronization burst,⁵ the initial steep raise of the neutrino luminosity,⁶ and the abrupt interruption of the neutrino signal due to a further collapse into a black hole⁷ have been used to this aim. However, there are some drawbacks to these methods: firstly only neutrinos with arrival time close to the

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benchmarks are used; secondly the observation of the benchmark events is not always certain, and in any case some model dependence on the details of the SN explosion is generally introduced. A new method that is free from these drawbacks was proposed in Ref. 8. The method relies only on the measurement of the neutrinos energies and arrival times and uses the full statistics of the detected signal. It is also remarkably independent of particular astrophysical assumptions since no use is made of benchmark events. The basic idea is the following: in the idealized case of vanishing experimental errors in the determination of the neutrino energies and arrival times, and assuming an arbitrarily large statistics and a perfectly black-body neutrino spectrum, one could use the events with energy above some suitable value E^* (to suppress the mass effects) to reconstruct very precisely the evolution in time of the neutrino flux and spectrum. Once the time dependence of the full signal is pinned down, the only parameter left to reconcile the time distribution of the low energy neutrinos with the high energy part of the signal would be the neutrino mass, that could then be nailed to its true value. Of course, none of the previous conditions is actually fulfilled. In Čerenkov detectors as SuperKamiokande (SK) the uncertainty in the energy measurement is important and must be properly taken into account. The statistics is large but finite, and finally, the SN neutrino spectrum is not perfectly thermal.⁹ Nevertheless, a good sensitivity to the mass survives, allowing to disentangle with a good confidence the case $m_\nu = 0$ from $m_\nu = 1$ eV.

The idea outlined above was tested in Ref. 8 by proceeding in two steps: *i*) First a set of synthetic neutrino signals is generated, according to a suitable SN model.¹⁰ Neutrinos are then propagated from the SN to the detector assuming two different mass values: $m_\nu = 0$ and 1 eV. *ii*) The detected signals are then analyzed with the aim of disentangling the two cases $m_\nu = 0$ and 1 eV. Only the SN-Earth distance is assumed to be known, while all other quantities, like the spectral functions and the detailed time evolution of the neutrino flux are inferred directly from the data.

For the time evolution of the neutrino flux and average energy the results of the SN explosion simulations given in Ref. 10 were used. The neutrino energy distribution was modeled by a Fermi-Dirac (FD) spectrum with time dependent spectral temperature $\hat{T}(t)$ and a ‘pinching’ factor $\hat{\eta}(t)$ introduced to account for spectral distortions⁹. Each neutrino is labeled by its emission time t_ν and by its energy E_ν , and the corresponding positron produced through the reaction $\bar{\nu}_e p \rightarrow e^+ n$ is also identified by a pair of values (E^e, t^e) generated by taking into account the detection cross section $\sigma(E_\nu)$ and the SK energy threshold and resolution.

The synthetic signals are then analyzed by means of the likelihood function

$$\mathcal{L} = S(\epsilon; T(t), \eta(t)) \times \Phi(t + \delta t; b, d, f) \times \sigma(\epsilon), \quad (2)$$

where ϵ is the neutrino energy inferred from the positron energy. The effective temperature $T(t)$ and pinching $\eta(t)$ of the FD spectral function S , and the detailed shape of the parametric function $\Phi(t + \delta t; b, d, f)$ that describes the neutrino flux are directly derived from the data.⁸ Given a value of m_ν the time delay of each neutrino is computed according to its energy ϵ_i , and subtracted from its arrival

Table 1. Results of the fits to the neutrino mass.

$E_{\text{tr}}:$	5 MeV		10 MeV	
$\hat{m}_\nu:$	0 eV	1 eV	0 eV	1 eV
$m_\nu^l > \hat{m}_\nu$ (%)	5 (11)	4 (5)	5 (10)	11 (5)
$m_\nu^u < \hat{m}_\nu$ (%)	9 (6)	2 (5)	12 (6)	10 (7)
$m_\nu^l > 0$ (%)	–	55 (40)	–	28 (23)

time t_i . For the new array of times $-\log \mathcal{L}$ is then evaluated, and minimized with respect to the flux shape parameters, until the value of the mass corresponding to the absolute minimum is found. The power of the method for disentangling $\hat{m}_\nu = 1$ eV from $\hat{m}_\nu = 0$ was studied by assuming in turn the two energy thresholds $E_{\text{tr}} = 5$ and 10 MeV, and two SN-Earth distances $L = 10$ and 20 kpc. For each case 40 samples were analyzed. Table 1 summarizes some of the results. The first row gives the percentage of times in which the 95% c.l. lower limit m_ν^l is *larger* than the input mass \hat{m}_ν . The second row refers to the cases when the upper limit m_ν^u is *smaller* than \hat{m}_ν . Number in parentheses correspond to $L = 20$ kpc. These figures characterize the percentage of ‘failures’ of the method, that therefore appears to be reliable in about 90%-95% of the cases. The third row gives the percentage of times when $m_\nu = 0$ is excluded at 95% c.l. when the signal is generated with $\hat{m}_\nu = 1$ eV. We see that for $E_{\text{tr}} = 5$ MeV and $L = 10$ kpc the method is successful in more than 50% of the cases. The results in table 1 were derived relying on two main simplifying approximations: 1) the neutrino energies were generated assuming a ‘pinched’ FD spectrum and fitted with a similar two-parameters energy distribution; 2) no effects of the neutrino oscillations were taken into account. The effects of these approximations have been analyzed in Ref. 8 by carrying out 40 simulations using the *numerical* spectra given in Ref. 9 and assuming a mixed $\bar{\nu}_e$ - $\bar{\nu}_\mu$ composite spectrum as would result from neutrino oscillations. It was found that even when the $\bar{\nu}_e$ - $\bar{\nu}_\mu$ spectral differences are assumed to be unrealistically large, the sensitivity of the method to the neutrino mass is only mildly affected.

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